Vector Boson productions and couplings at LEP2

- Introduction
- L3 Detector
- Signal Definition
- Event Selection
- Results and Discussion
- Summary

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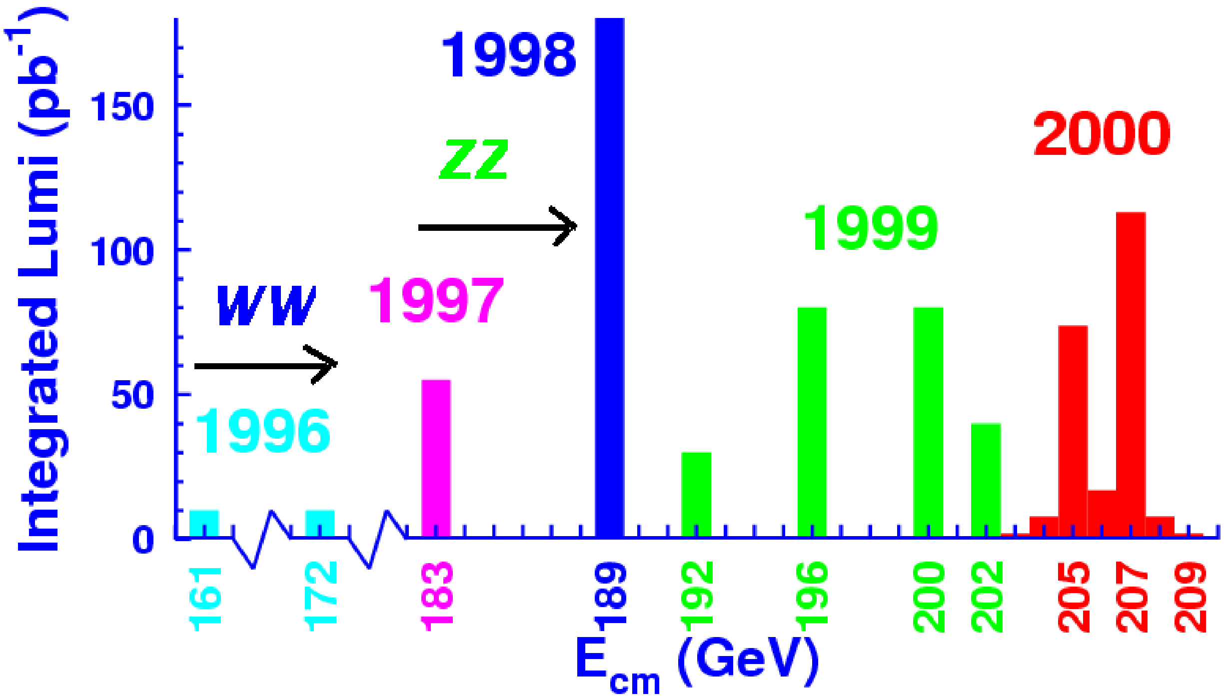
Motivation

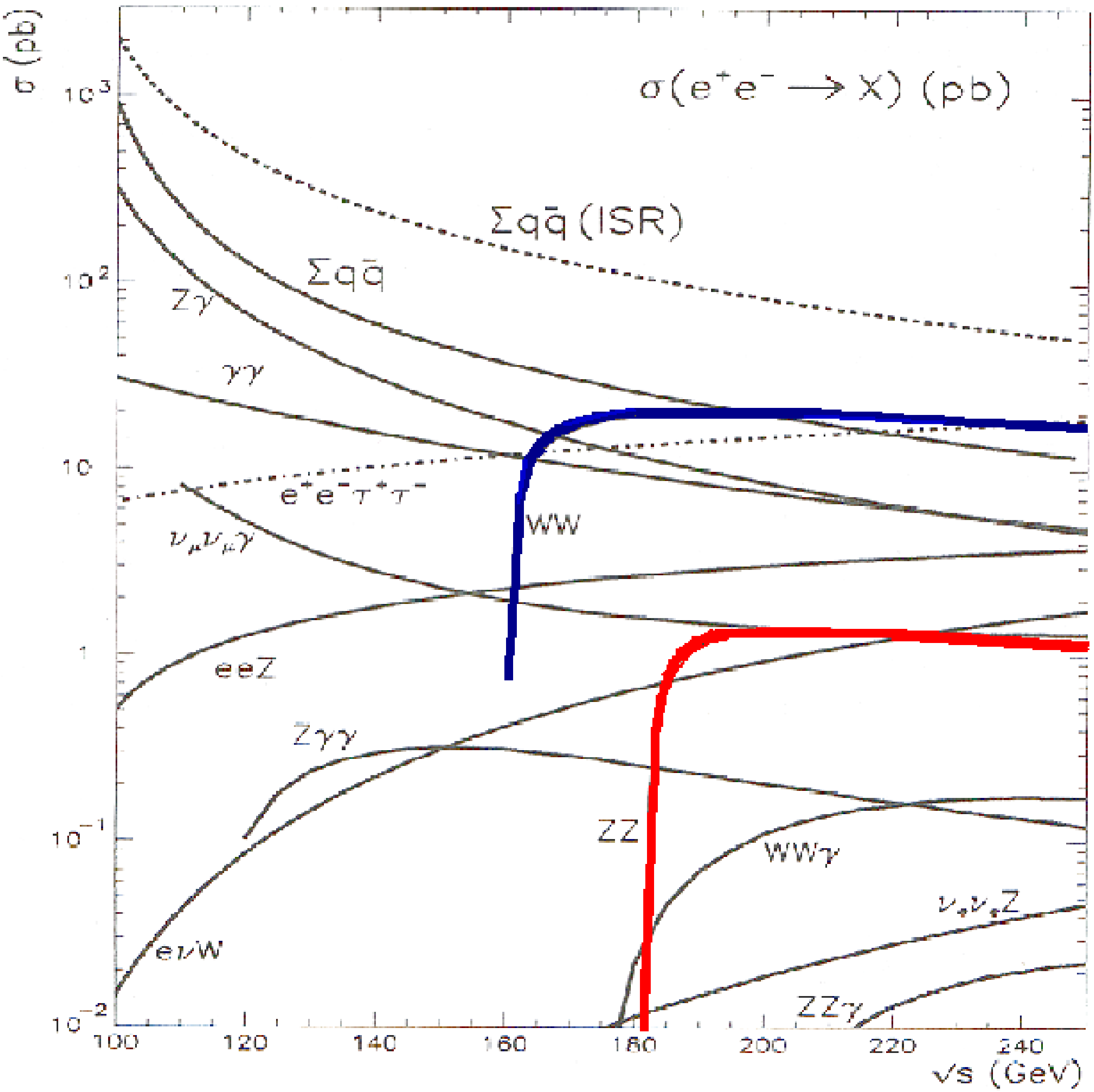
- Interactions between gauge bosons; $W^{\pm}$, Z and γ are a direct consequence of the non-abelian nature of Standard Model
- Vector boson pair productions (W^+W^-, ZZ) offer unique possibilities to study various possible gauge-boson couplings
- Any deviation from S.M. expectation in the form of:
  - ➠ Enhancement on the cross section
  - ➠ Change in angular distribution

  can be attributed to the presence of anomalous Trilinear Gauge Couplings (TGC) or Quartic Coupling (QGC)

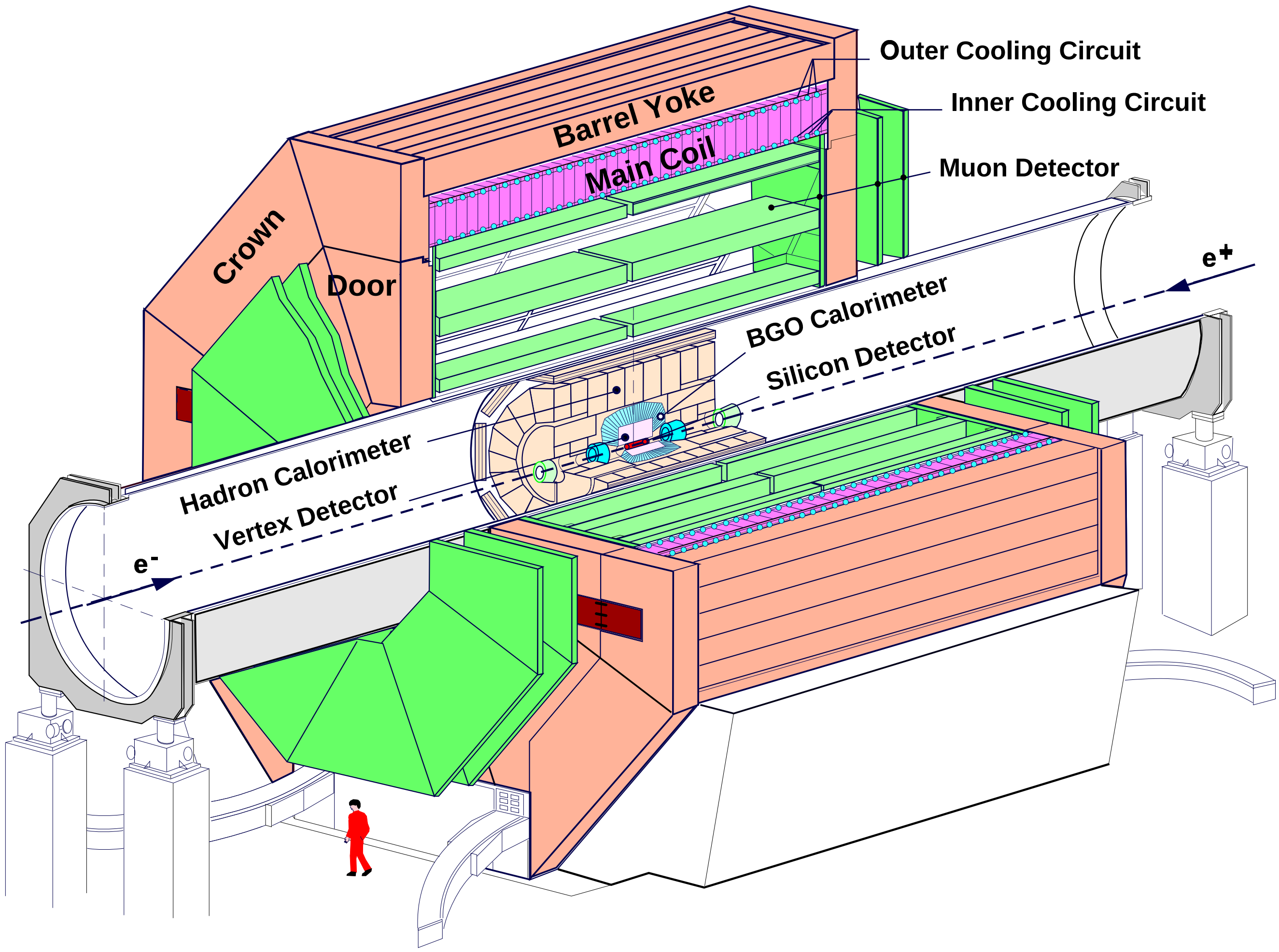


- LEP is an ideal place to precisely measure the cross section for vector boson pair production, and the couplings

Physics process in e^+e^- collision



☞ W^+W^- and ZZ events, in particular have to be selected out of a sea of competing processes



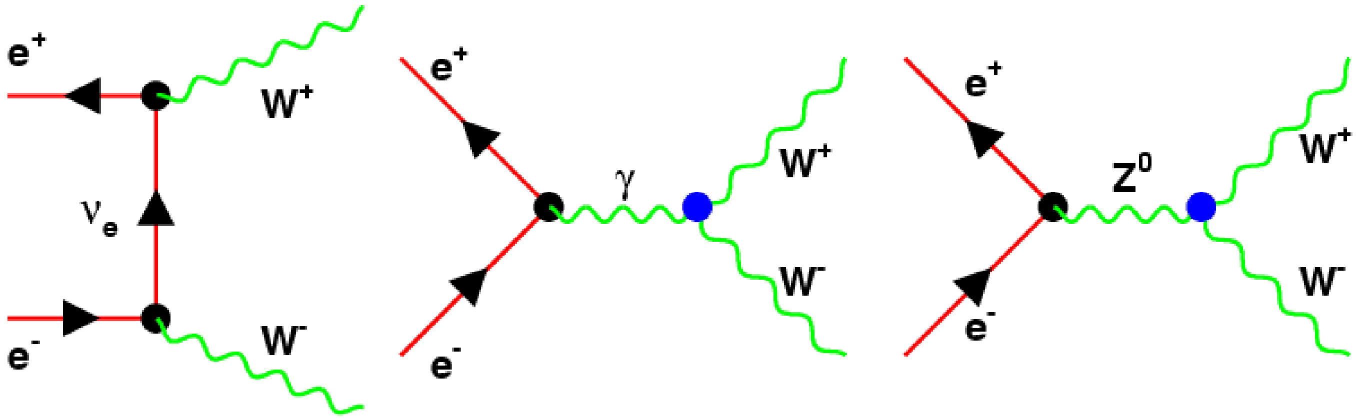
- L3 detector is one of the four LEP experiments
- High resolution for Photons/Electrons and Muons
- Good hermiticity for jet and $\not{\vec{P}}$ reconstruction

Focus of my talk

✝ 2000 data: $217 pb^{-1}$ @ $\sqrt{s} = 201$ - 209 GeV
✝ 1999 data: $233 pb^{-1}$ @ $\sqrt{s} = 192$ - 202 GeV

WW Production

☞ As Standard Model predicts



☞ Extended to the more general Lorentz invariant form

$$
\begin{aligned}
\frac{i\mathcal{L}_{eff}^{WWV}}{g_{WWV}} = & \; g_1^V V^\mu (W_{\mu\nu}^- W^{+\nu} - W_{\mu\nu}^+ W^{-\nu}) + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} \\
& + \frac{\lambda_V}{m_W^2} V^{\mu\nu} W_\nu^{+\rho} W_{\rho\mu}^- + i g_4^V W_\mu^+ W_\nu^- (\partial^\mu V^\nu + \partial^\nu V^\mu) \\
& + i g_5^V \epsilon_{\mu\nu\rho\sigma} ((\partial^\rho W^{-\mu}) W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu})) V^\sigma \\
& - \frac{\tilde{\kappa}_V}{2} W_\mu^- W_\nu^+ \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_V}{2m_W^2} W_{\rho\mu}^- W_\nu^{+\mu} \epsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}
\end{aligned}
$$

☞ Too many parameters to be measured simultaneously

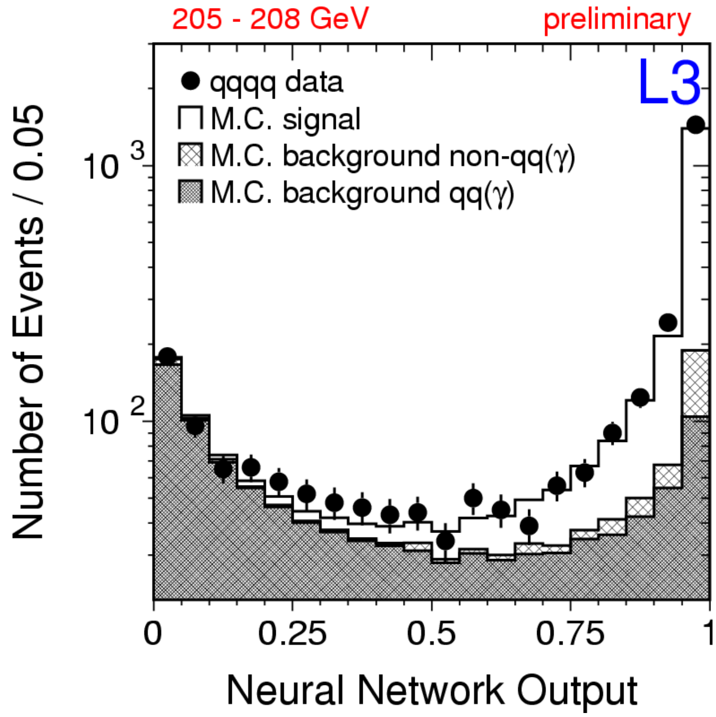
- ☆ Require C, P and CP conservation
- ✪ Require $U(1)_{em}$ gauge invariance ($g_1^\gamma \Rightarrow q_W = \pm 1$)
- ★ Still five parameters left with: $g_1^Z, \kappa_\gamma, \kappa_Z, \lambda_\gamma, \lambda_Z$
- ✯ Further reduction requires $\underbrace{SU(2)_L \bigotimes U(1)_Y}$ symmetry

❶ $\kappa_Z = \kappa_\gamma \; tan^2\theta_W$	$\kappa_Z = \kappa_\gamma = 1$ **(SM)**
❷ $\lambda_Z = \lambda_\gamma$	$\lambda_Z = \lambda_\gamma = 0$ **(,,)**
❸ g_1^Z	$g_1^Z = 1$ **(,,)**

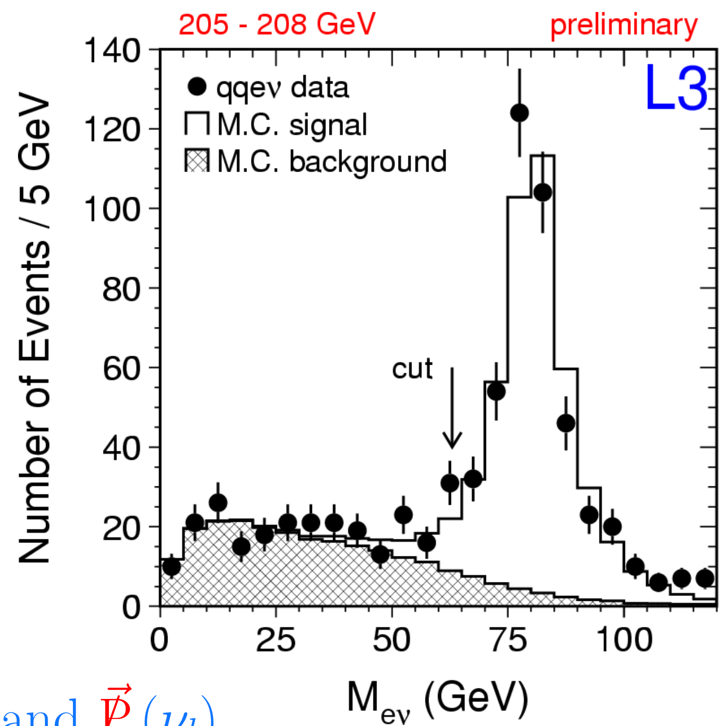
Event Selection

WW Events

- 46% $q\bar{q}'q'\bar{q} \Rightarrow$ Four jets
  - ➠ Fully balanced event
  - ➠ Large multiplicity
  - ➠ Bkg from $q\bar{q}(\gamma)$, ZZ
  - ➠ NN-based selection



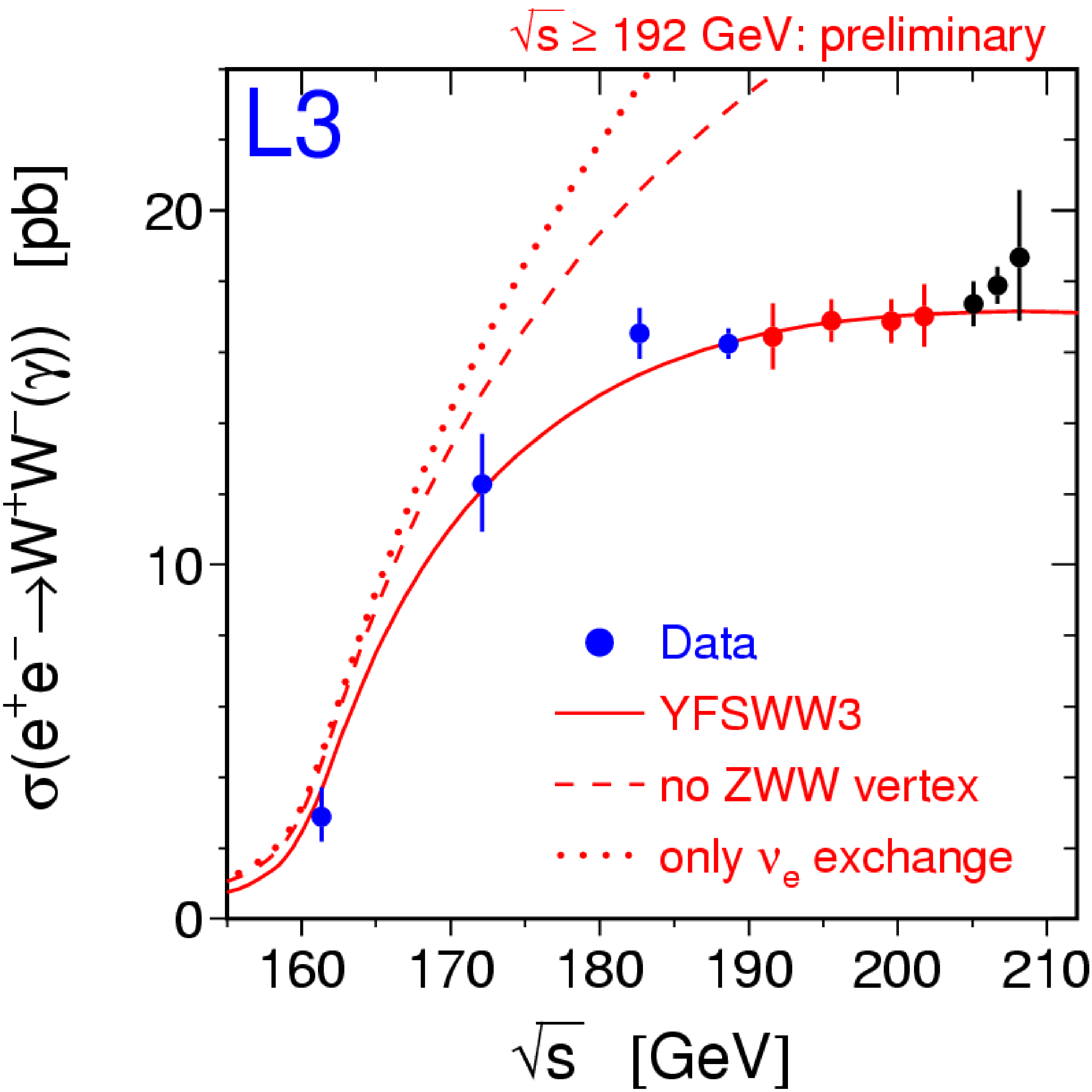
- 44% $q\bar{q}'l\nu \Rightarrow$ Two jets, one lepton and $\not\vec{P}\,(\nu_l)$
  - ➠ Well isolated lepton
  - ➠ Large multiplicity
  - ➠ Cut-based selection

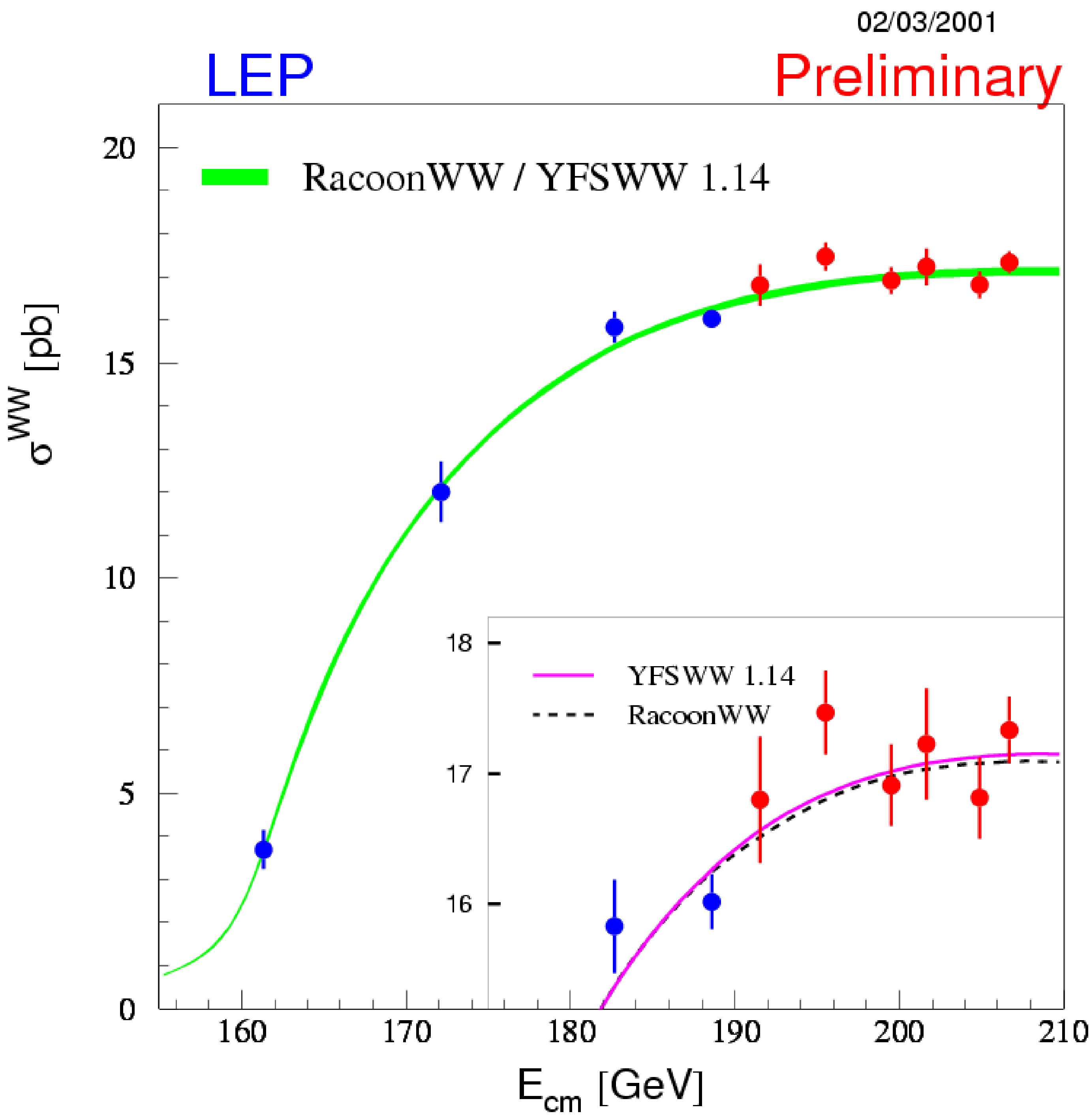


- 10% $l\bar{\nu}\bar{l}'\nu' \Rightarrow$ Two leptons and $\not\vec{P}\,(\nu_l)$
  - ➠ Ask for 2 energetic and acoplanar leptons
  - ➠ Reject hadronic events using multiplicity

WW Production Cross section

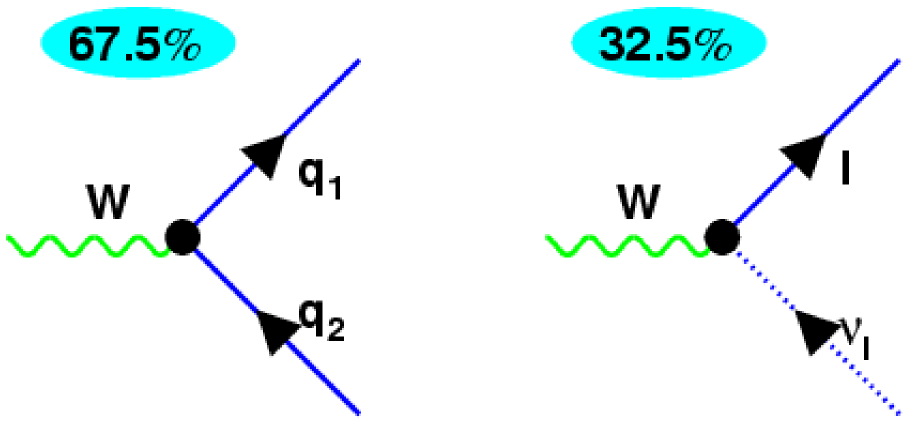
- σ_{WW} is determined by fitting the total likelihood which is the product of $\mathcal{P}(N_i, \mu_i)$ for each i-th process





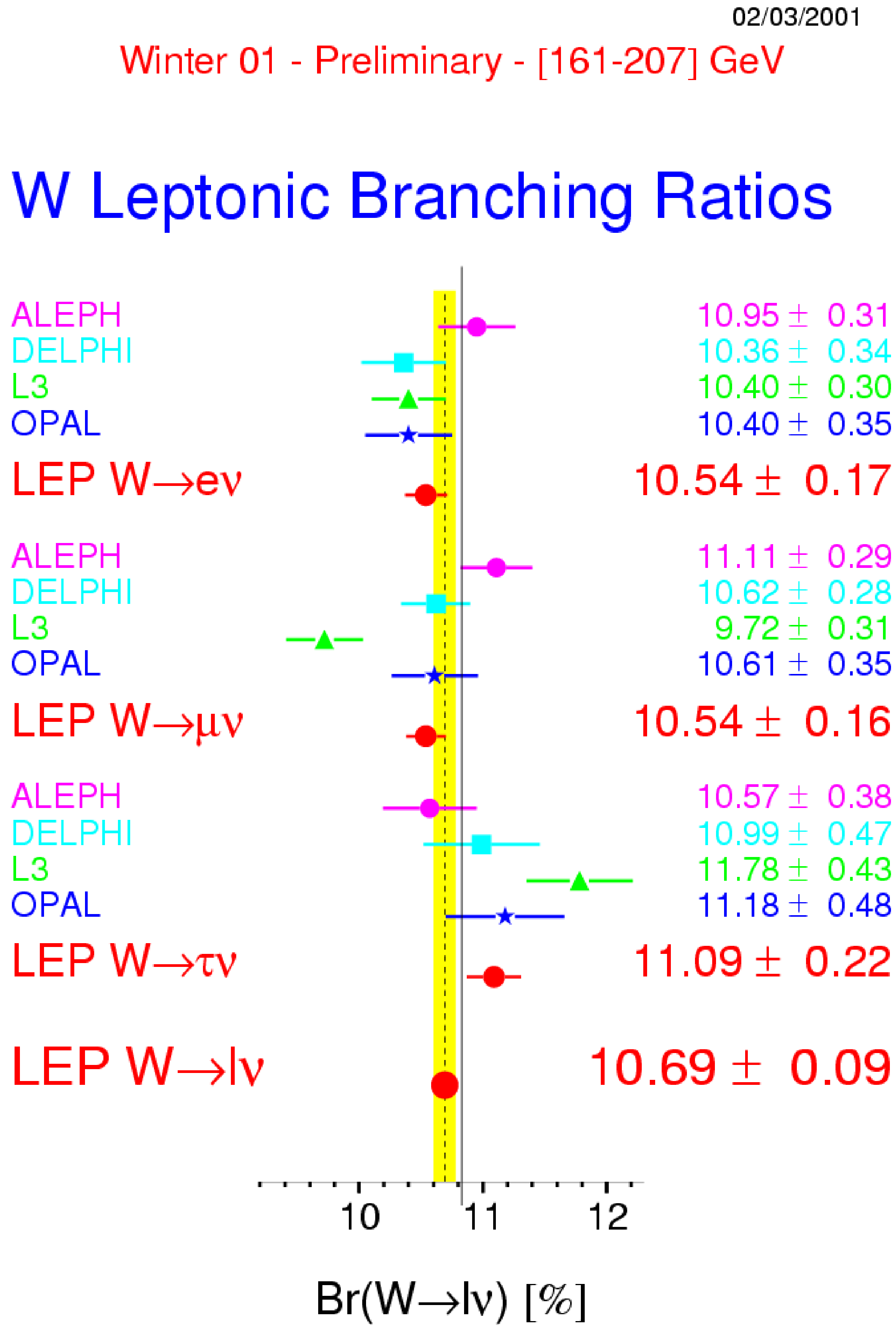
✔ σ_{WW} already puts stringent constraints on TGC excluding models without ZWW and γWW vertex

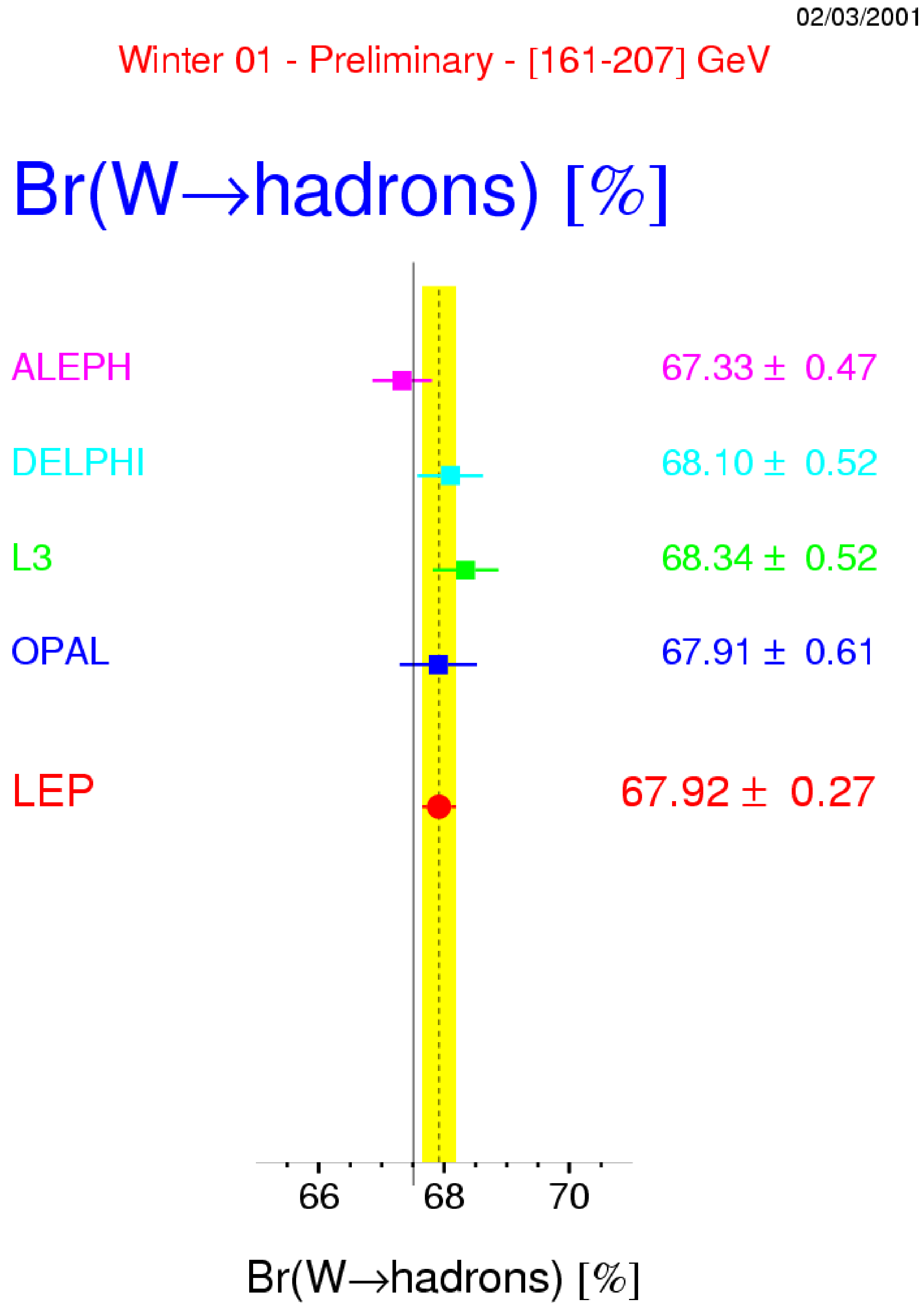
W-Decay Branching Fractions



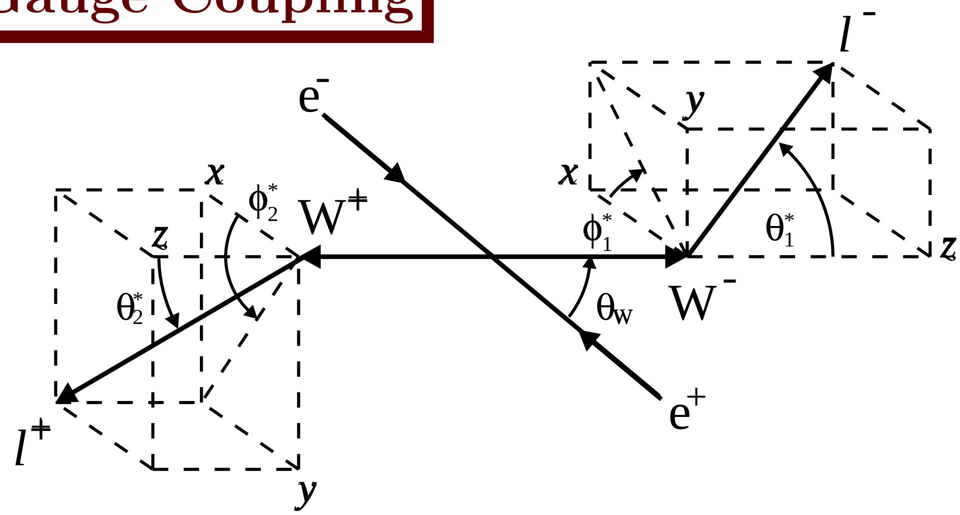
- σ_i for signal process i is $r_i \sigma_{WW}$, with r_i given in terms of hadronic and leptonic B.F. of W
  - $r_{qqqq} = [B(W \to qq)]^2$
  - $r_{qql\nu} = 2B(W \to qq)B(W \to l\nu)$
  - $r_{l\nu l\nu} = [B(W \to l\nu)]^2$
  - $r_{l\nu l'\nu'} = 2B(W \to l\nu)B(W \to l'\nu')$
- Sum of the hadronic and leptonic B.F. is constrained to unity

Branching Fraction[%]	Lepton Non-Universality	Lepton Universality
$W \to e\nu$	$10.40 \pm 0.26 \pm 0.14$	-
$W \to \mu\nu$	$9.72 \pm 0.27 \pm 0.15$	-
$W \to \tau\nu$	$11.78 \pm 0.38 \pm 0.21$	-
$W \to l\nu$	-	$10.55 \pm 0.13 \pm 0.11$
$W \to qq$	$68.10 \pm 0.41 \pm 0.33$	$68.34 \pm 0.40 \pm 0.33$

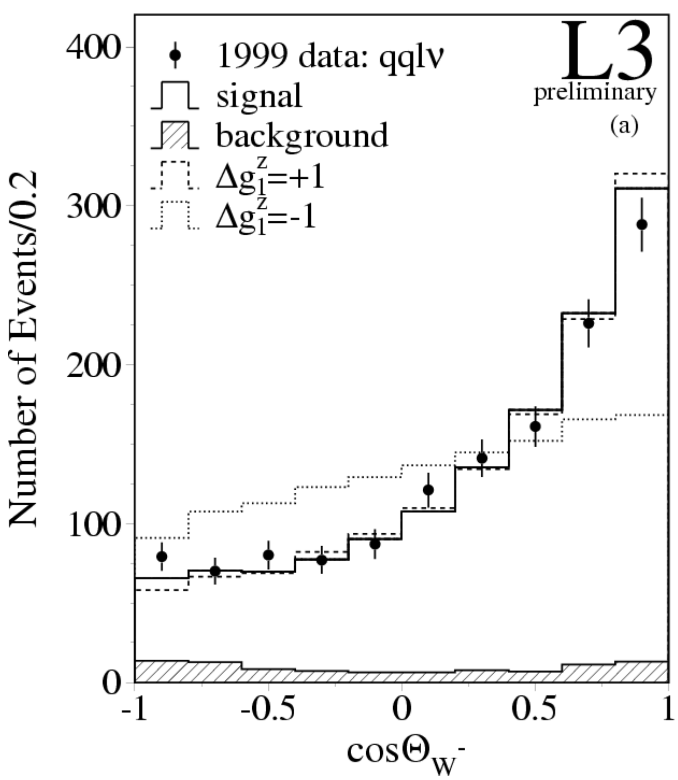

02/03/2001
Winter 01 - Preliminary - [161-207] GeV
W Leptonic Branching Ratios
ALEPH 10.95 ± 0.31
DELPHI 10.36 ± 0.34
L3 10.40 ± 0.30
OPAL 10.40 ± 0.35
LEP W→eν 10.54 ± 0.17
ALEPH 11.11 ± 0.29
DELPHI 10.62 ± 0.28
L3 9.72 ± 0.31
OPAL 10.61 ± 0.35
LEP W→μν 10.54 ± 0.16
ALEPH 10.57 ± 0.38
DELPHI 10.99 ± 0.47
L3 11.78 ± 0.43
OPAL 11.18 ± 0.48
LEP W→τν 11.09 ± 0.22
LEP W→lν 10.69 ± 0.09
10
11
12
Br(W→lν) [%]

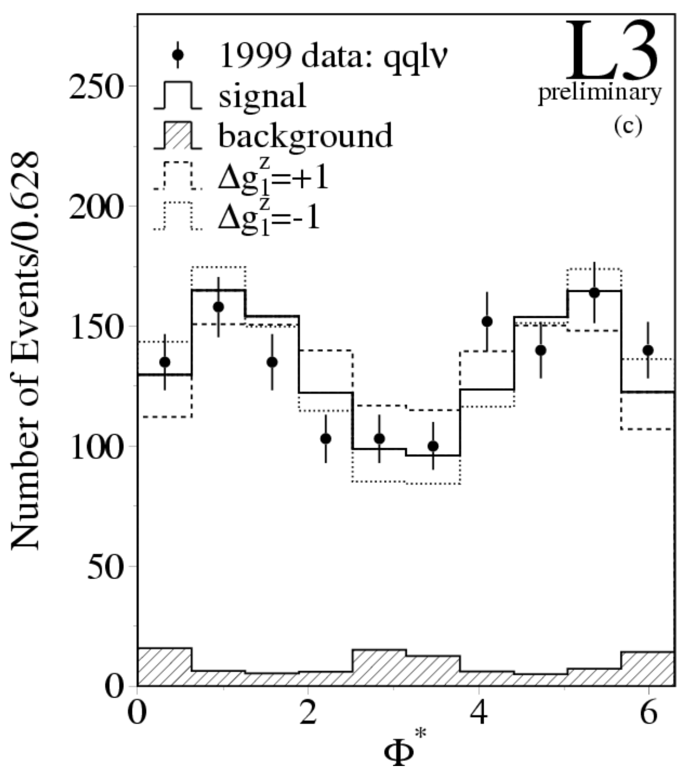

02/03/2001
Winter 01 - Preliminary - [161-207] GeV
Br(W→hadrons) [%]
ALEPH
67.33 ± 0.47
DELPHI
68.10 ± 0.52
L3
68.34 ± 0.52
OPAL
67.91 ± 0.61
LEP
67.92 ± 0.27
66
68
70
Br(W→hadrons) [%]

Triple Gauge Coupling

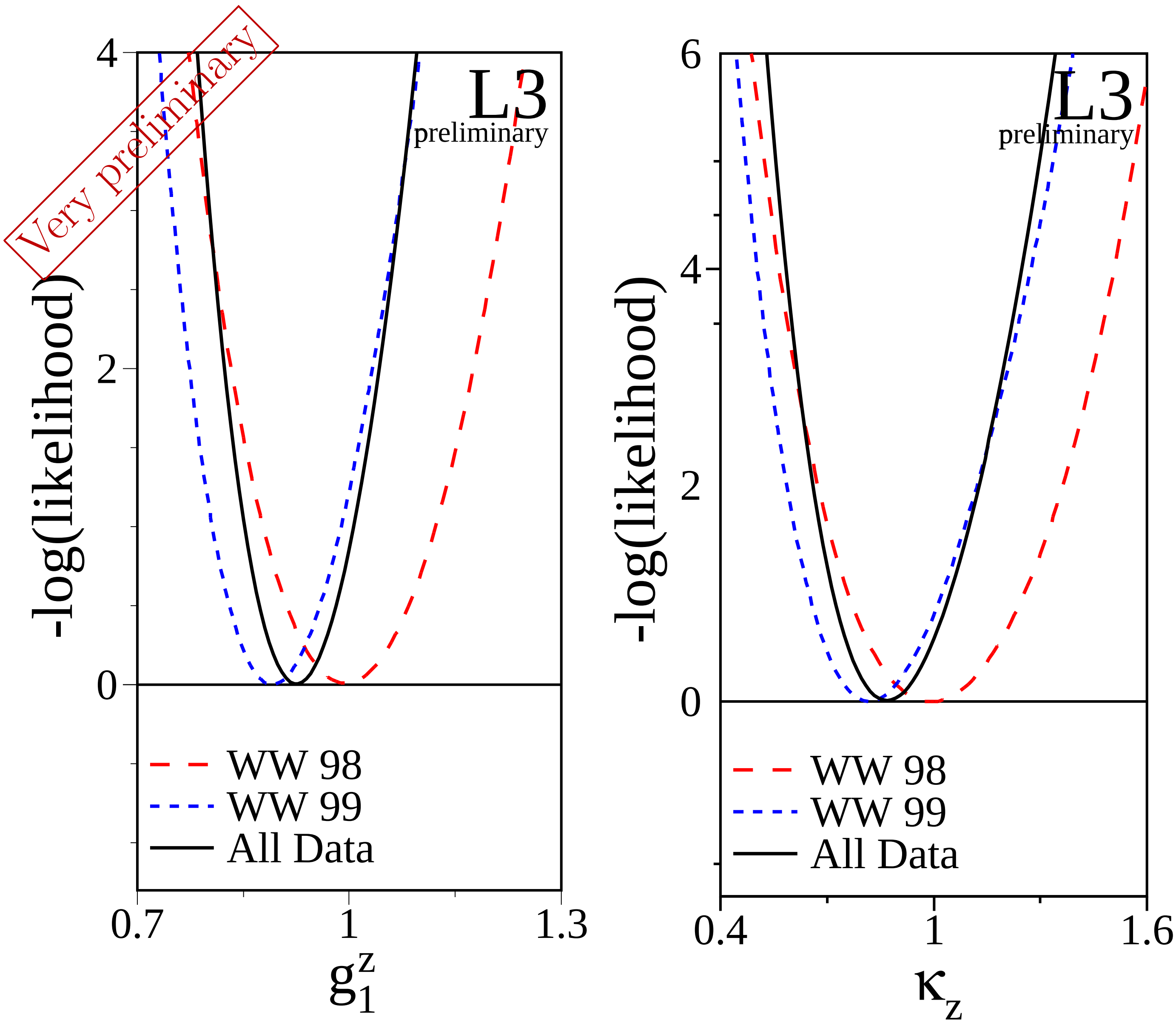


- Use W-decay as the polarimeter
  - ➠ $cos\theta_W$, the decay polar angle of the W^-
  - ➠ $cos\theta_1^*, \phi_1^*$ of the fermion in the W^- rest-frame
  - ➠ $cos\theta_2^*, \phi_2^*$ of the anti-fermion in the W^+ rest-frame





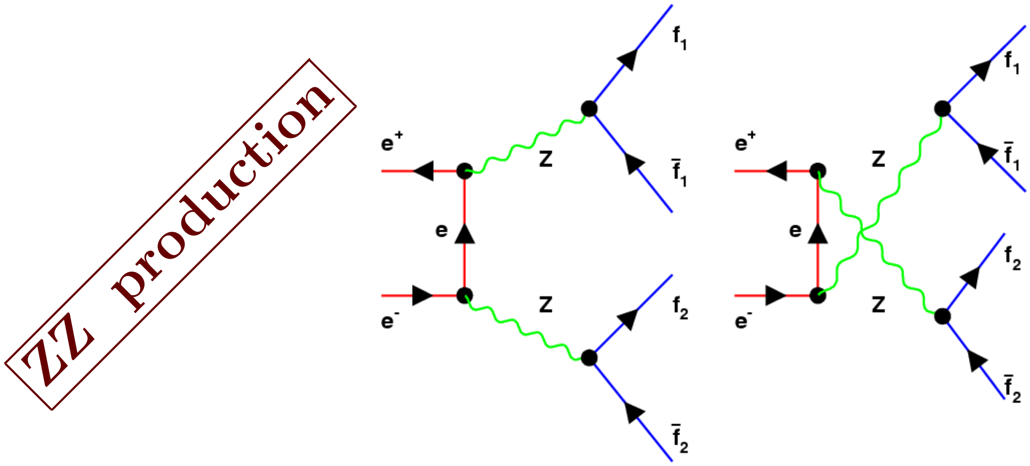
- $cos(\theta_W)$: Highest sensitivity to TGC
- Sensitivity increasing with $\sqrt{s}$



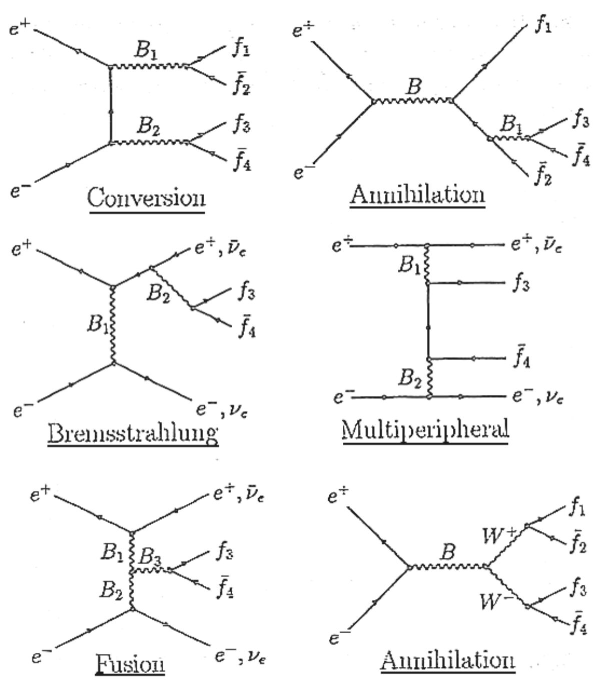
Limits on TGC

$0.82 < g_1^Z < 1.04$	$-0.34 < \lambda_Z < 0.16$
$0.66 < \kappa_Z < 1.12$	$-0.19 < \lambda_\gamma < 0.05$
$0.73 < \kappa_\gamma < 1.20$	$-0.52 < g_5^Z < 0.42$

- Z-pair production is mainly via t and u channel electron exchange (Neutral Current 02 diagram)

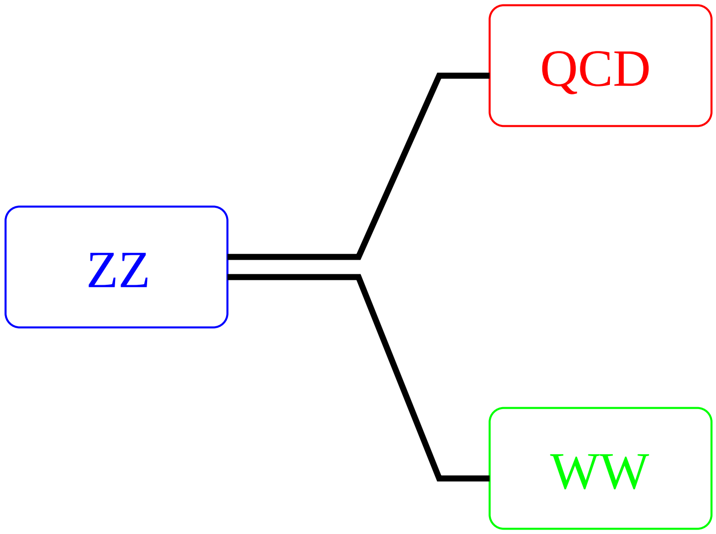


- Other potential sources of 4-fermion final states



- Define phase space cuts
  - $M_{f_1\bar{f}_1,f_2\bar{f}_2} \in$ 70-105 GeV *vs.* γ^* exchange
  - $M_{f_1\bar{f}_2,f_2\bar{f}_1} \notin$ 75-85 GeV *vs.* WW production
  - $|\cos\theta_{\rm e}| < 0.95$ *vs.* Multi-peripheral diagram

$ZZ \rightarrow q\bar{q}q\bar{q}$ (Neural Network approach)



} Topological Variable

- Min. jet opening angle
- Max & Min Jet energy
- Spherocity

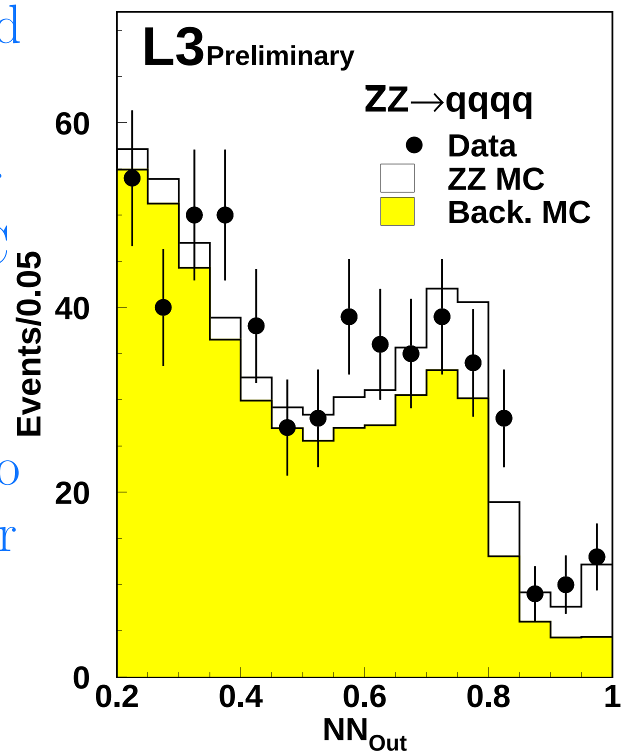
etc...

} Specific Jet Variable

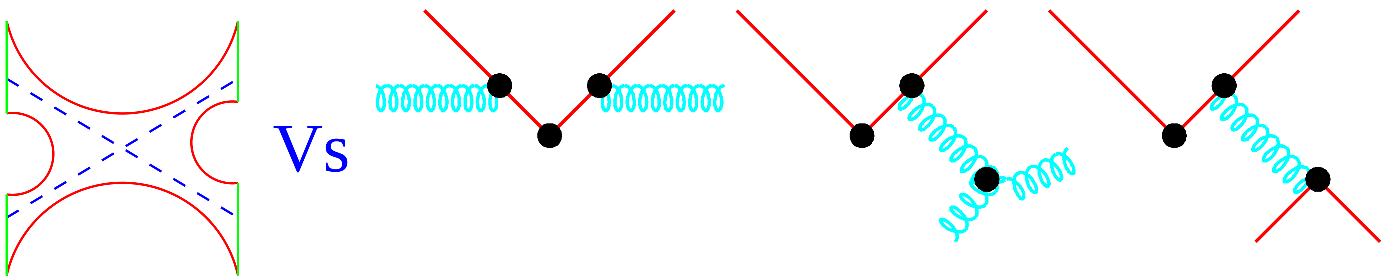
- Di-jet mass sum / diff.
- Average # tracks / Jet
- B-tag discriminant

etc...

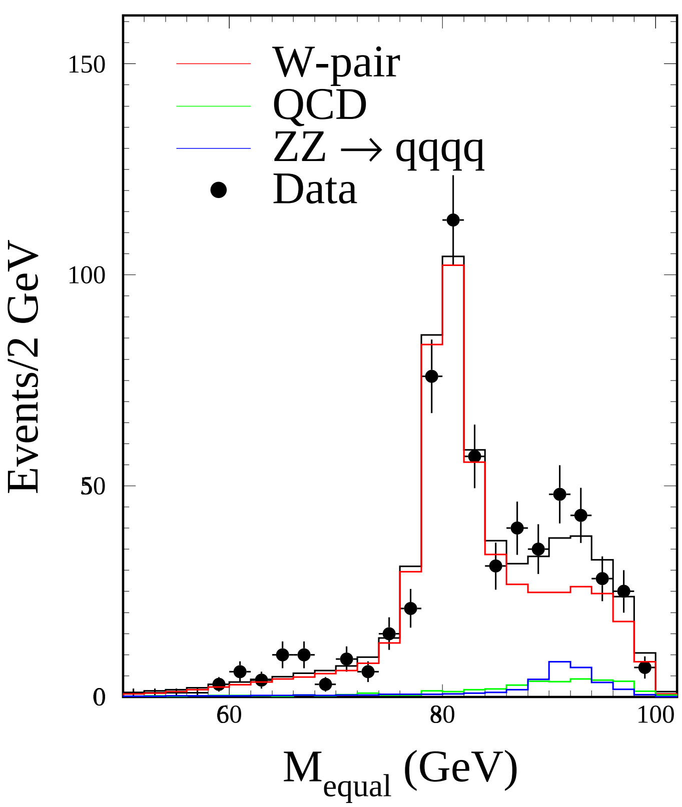
- Preselection requiring high multiplicity and well balanced events
- Force the calorimetric cluster to form four jets and do a 4C fit requiring conservation of energy-momentum
- Train two Neural Networks to take care of QCD and W-pair

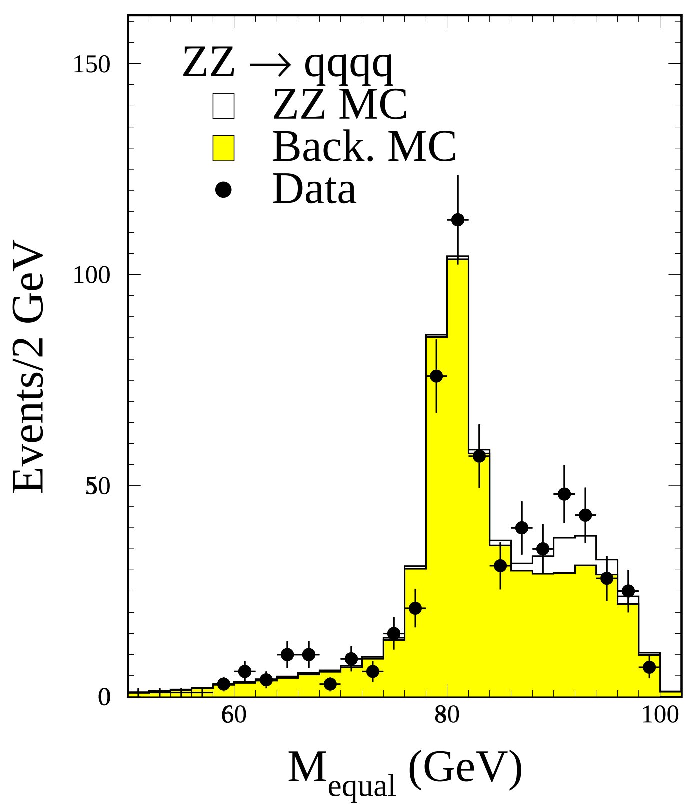


ZZ → $q\bar{q}q\bar{q}$ (Special Physics Variables)



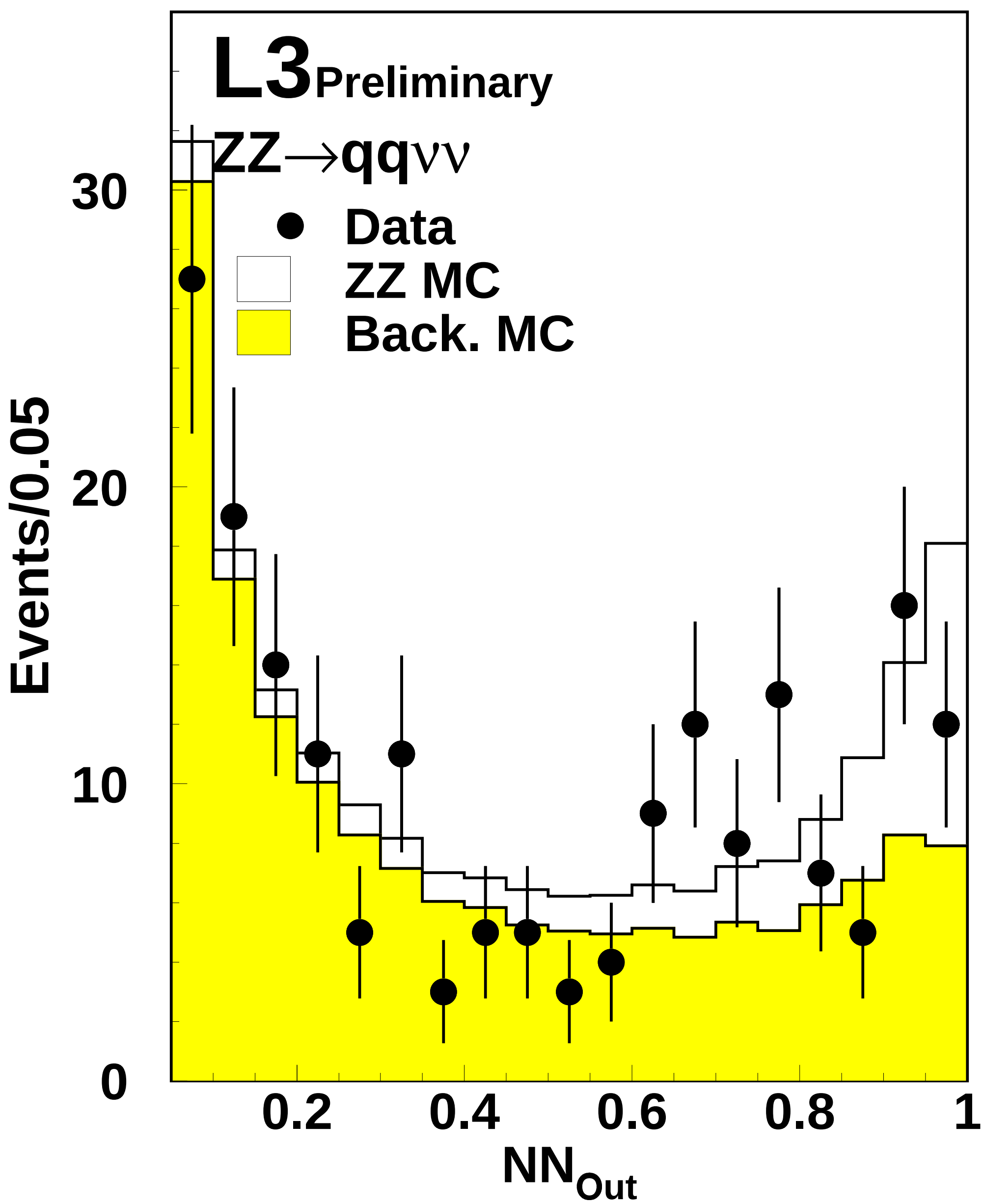
- Pair the jets as 1st, 2nd and 3rd pair with increasing $\Delta\gamma$
- Find out $(\gamma_{L2} + \gamma_{L3})$, the larger boosts for 2nd and 3rd pair
- Define triple jet boost: $max(\gamma_{123}, \gamma_{134}, \gamma_{234})$ with $\gamma_{ijk} = \frac{E_{ijk}}{M_{ijk}}$
- Restrict on these two Sp. Phy. Var. to cut down QCD bckg
- Extract ZZ cross-section fitting the resultant mass spectrum





$ZZ \longrightarrow q\bar{q}\nu\bar{\nu}$

- Though reasonably high statistics has to suffer from huge background comprising of single W/Z production and QCD
- After trivial preselection a Neural Network is trained plugging in various kinematical and topological variables



Event Selection

$ZZ \rightarrow q\bar{q}\ell^+\ell^-$

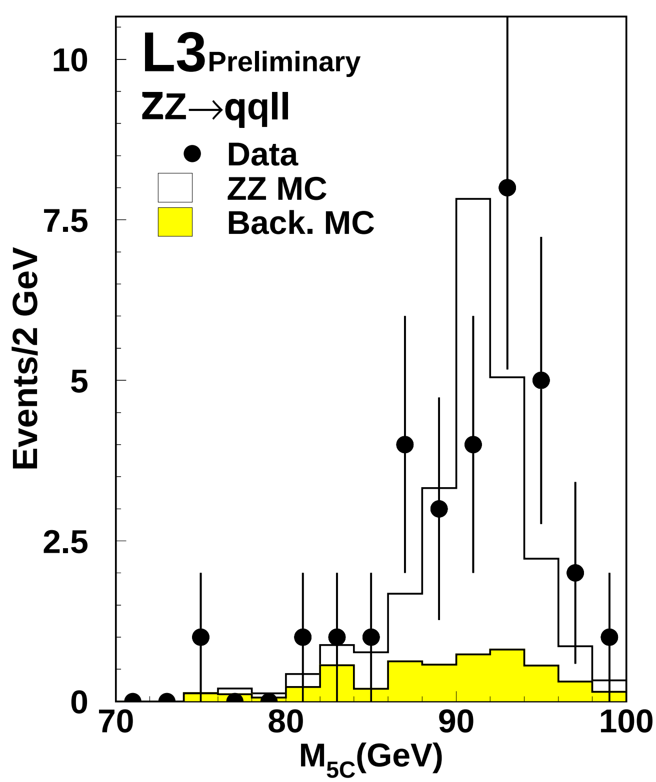
- Clean channel with two identified leptons and hadronic jets
- Statistics is quite poor because of small branching ratio
- Algorithm has to be optimised keeping proper balance between lepton identification and kinematic requirement

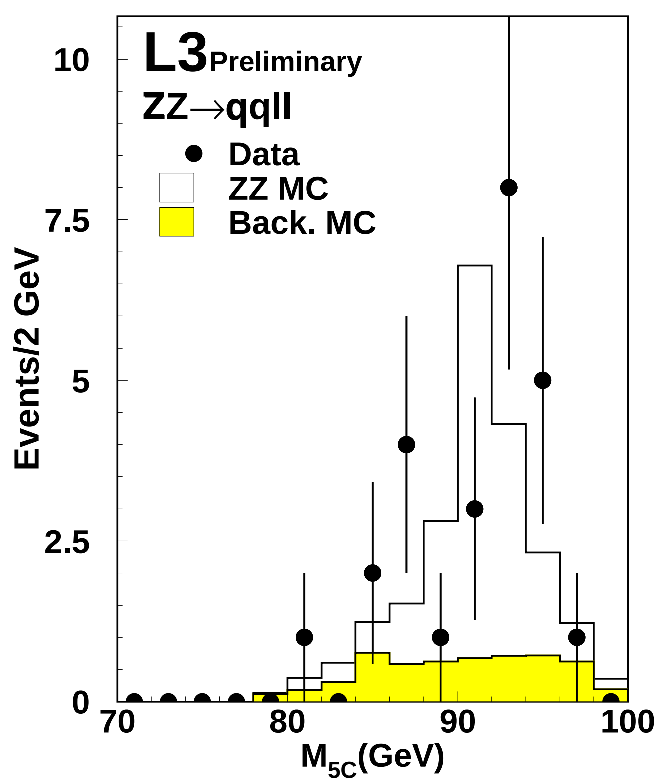
☞ Lepton Identification

- well isolated $e(\gamma)$, μ(MIP) or hadronic τ seen as a narrow deposition of energy with low track/cluster multiplicity

☞ Kinematic requirement

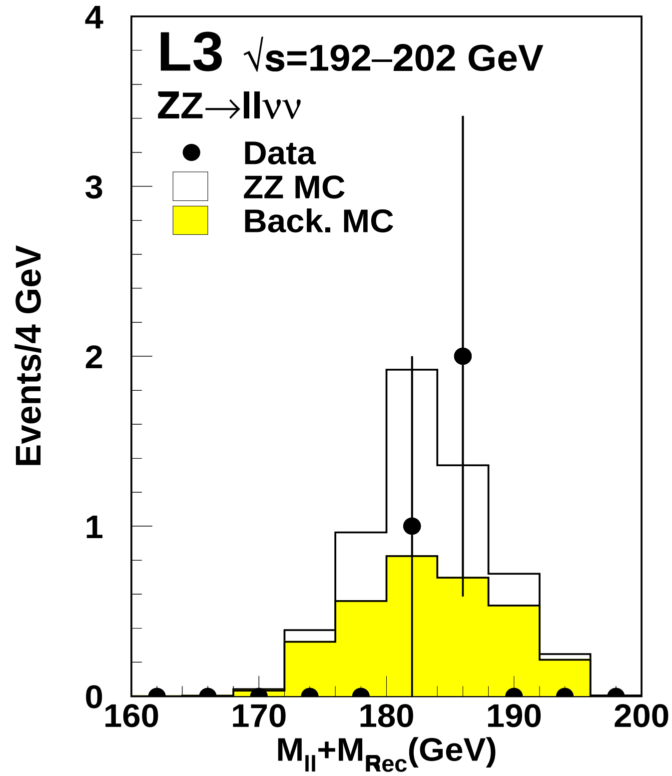
- Require m_{ll} and m_{jj} to be close to m_Z
- Additional constraint on α_{ll} and α_{jj}





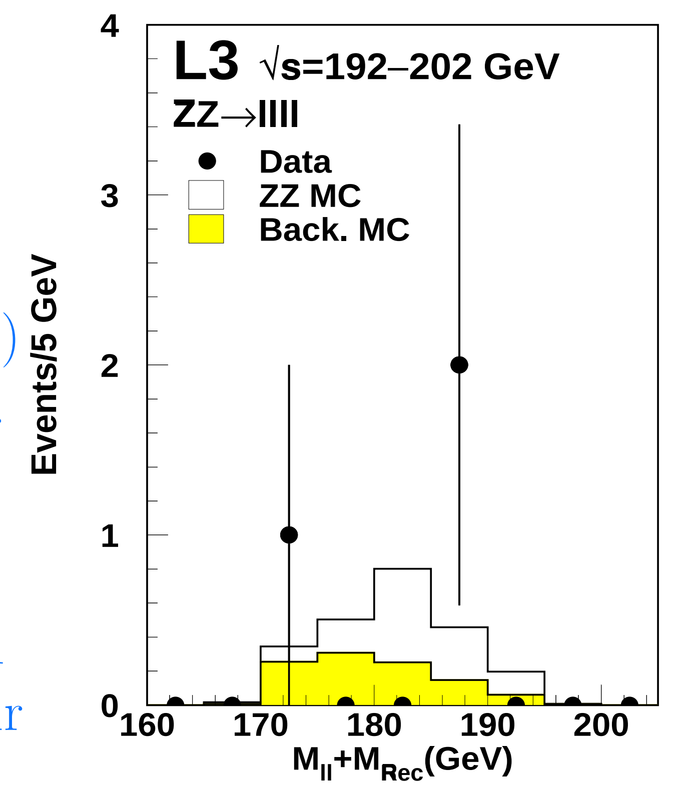
$ZZ \to \ell^+\ell^-\nu\bar{\nu}$

- Two same flavour leptons and missing neutrinos
- Main background: Fermion pair & non-reso processes
- Dilepton and recoil mass should be close to m_Z
- Also cut on acolinearity & acoplanarity

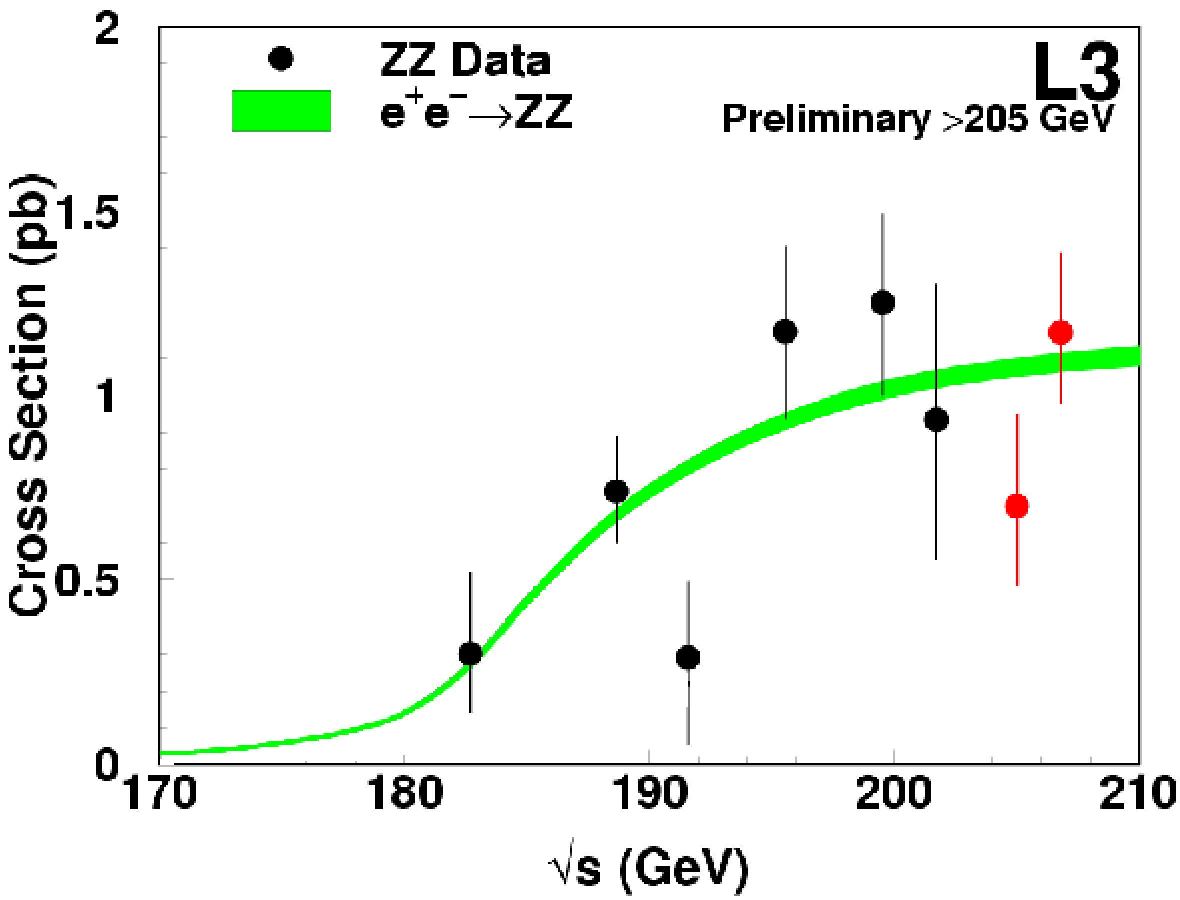


$ZZ \to \ell^+\ell^-\ell^+\ell^-$

- Cleanest channel with well balanced topology and low multiplicity
- Lowest branching ratio(2%)
- Best lepton-pair is the pair with m_{ll} closest to m_Z for same flavour leptons
- Cut on invariant and recoil mass of the best lepton pair

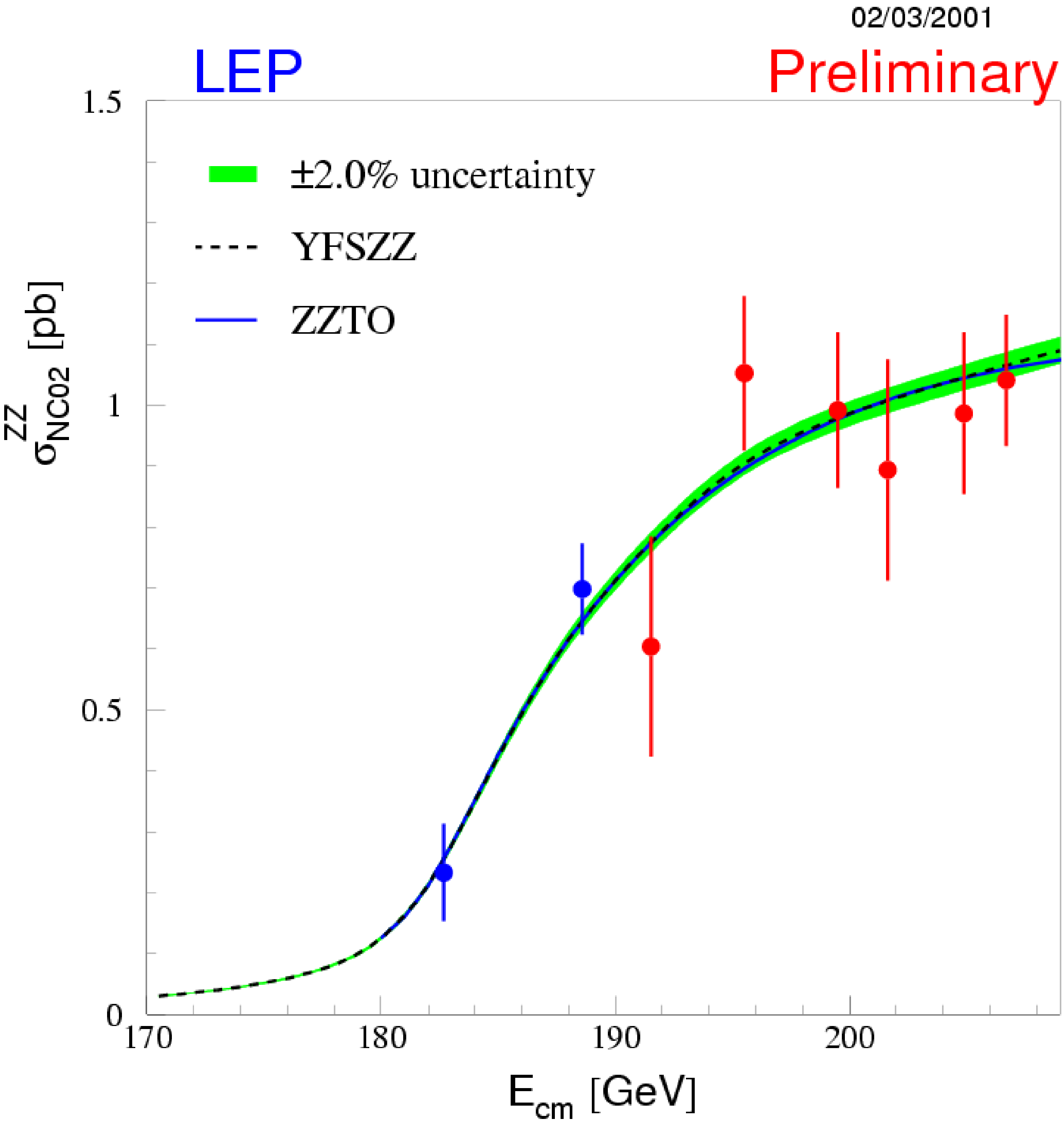


ZZ Production Cross section



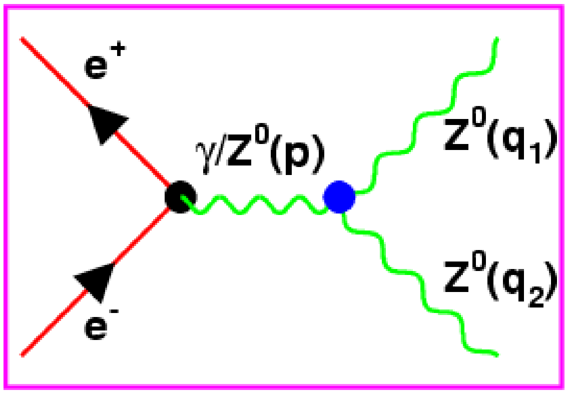
$\sqrt{s}$(GeV)	σ^{SM}(pb)	$\sigma^{measured}$(pb)	$\mathcal{R} = \frac{\sigma^{NC02}}{\sigma^{cut}}$
192	0.79	$0.29 \pm 0.22 \pm 0.02$	1.0000
196	0.92	$1.17 \pm 0.24 \pm 0.09$	1.0085
200	1.00	$1.25 \pm 0.25 \pm 0.09$	1.0000
202	1.03	$0.93 \pm 0.38 \pm 0.07$	1.0215
205	1.07	$0.70\ ^{+0.25}_{-0.22}$	0.9857
207	1.08	$1.18\ ^{+0.21}_{-0.20}$	0.9915

LEP-wide result



Anomalous Couplings from Z-pair

???



$$-i\Gamma^{\alpha\beta\mu}_{ZZV}(q_1, q_2, p) = \frac{s-m_V^2}{m_Z^2}\left(f_4^V(p^\alpha g^{\mu\beta}+p^\beta g^{\mu\alpha})+f_5^V\epsilon^{\mu\alpha\beta\rho}(q_1-q_2)_\rho\right)$$

f_4^V (CP-violating) and f_5^V (CP-conserving) are absent in SM

- To find out the impact of non-zero f_4^V and f_5^V:
  - Re-weight MC sample including Anomalous Couplings
  - Maximum likelihood fit to the most significant distribution
  - Repeat the exercise for each f_i^V, fixing others to zero

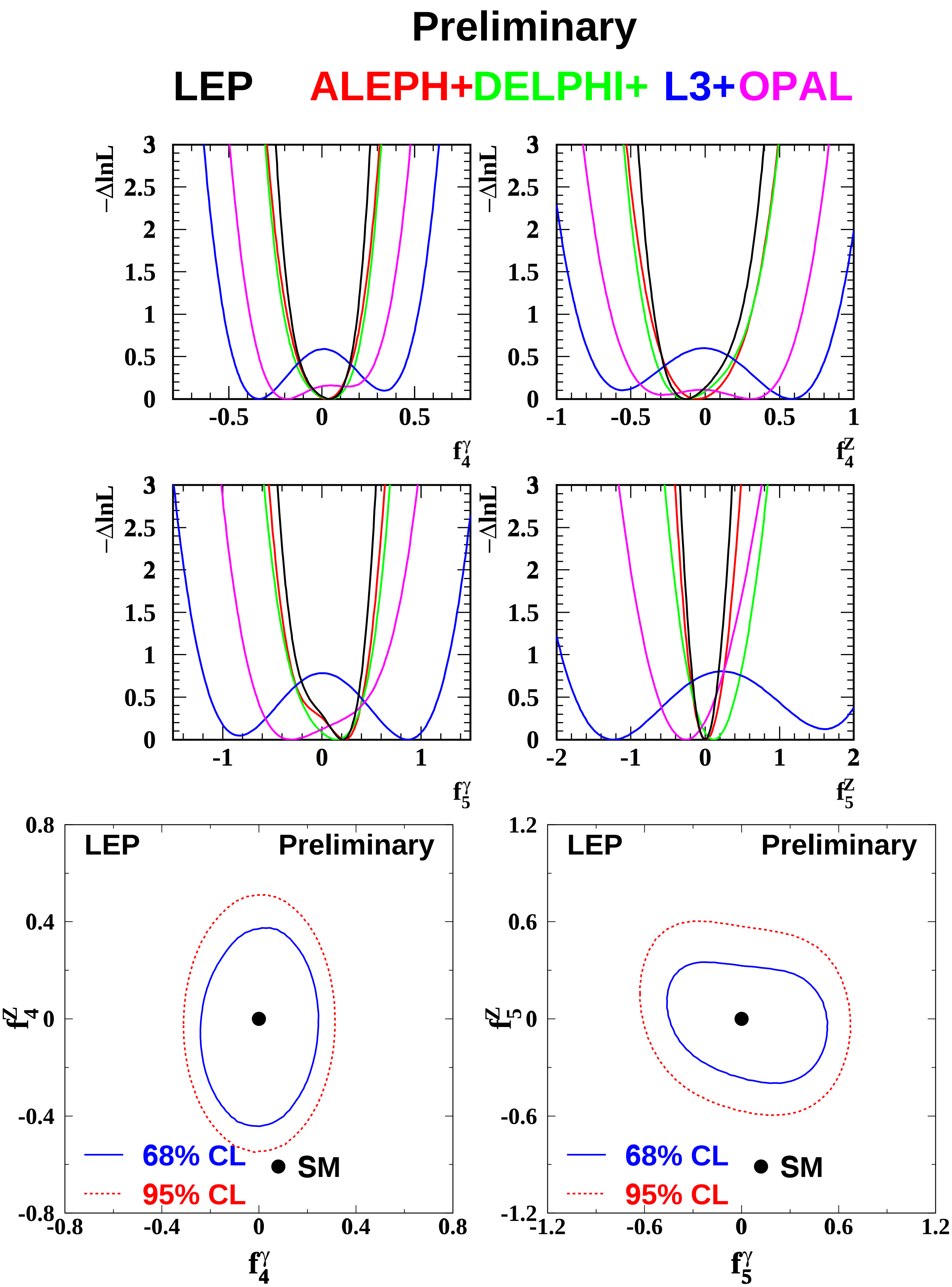
95 % C.L. limits

$-0.68 \leq f_4^Z \leq 0.68$

$-1.03 \leq f_5^Z \leq 1.13$

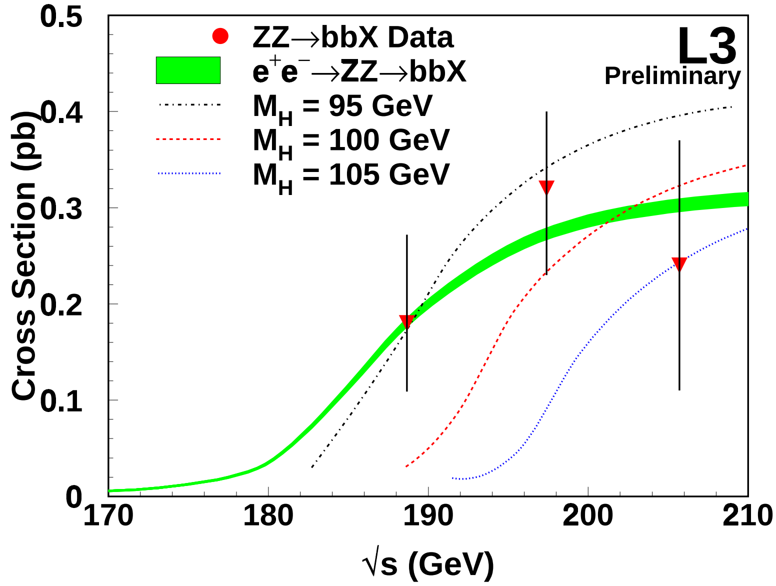
$-0.40 \leq f_4^\gamma \leq 0.40$

$-0.84 \leq f_5^\gamma \leq 0.87$

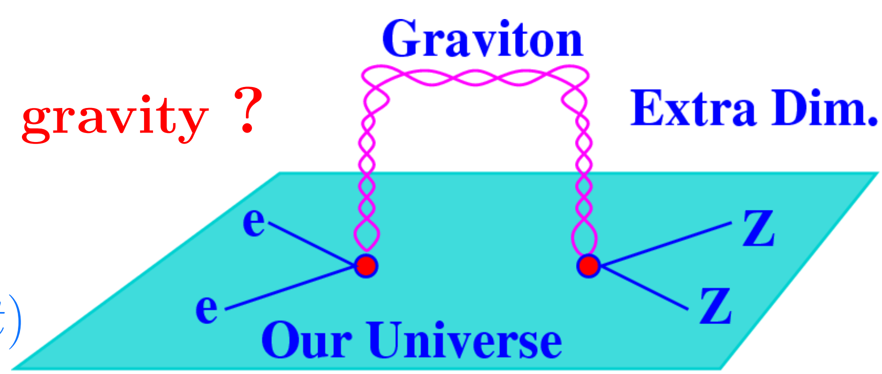

Preliminary
LEP ALEPH+DELPHI+ L3+OPAL
−ΔlnL
f4γ
f4Z
f5γ
f5Z
LEP Preliminary
68% CL
95% CL
SM

Benchmark to Higgs at LEP

- Verifies the capability of our detector to discover Higgs
- Because of identical final states and similar value of cross section



☞ **And how about gravity ?**



$$\frac{d\sigma}{d\Omega}(s,t) = \frac{d\sigma^{SM}}{d\Omega}(s,t) + \frac{\lambda}{M_S^4}\,\alpha_{Inter}(s,t) + \frac{\lambda^2}{M_S^8}\,\beta_{LSG}(s,t)$$

✎ Fit to the σ^{ZZ} or angular information

✎ Extract 95% C.L. lower limits on M_S:

λ = -1	λ = +1
1.2 TeV	1.2 TeV

Summary

- Over the past several years, extreme precision measurement and new energy frontier have been the trade marks of LEP
- Here we have discussed a particular case of vector boson pair productions and various possible gauge-boson couplings
- All our results, are in excellent agreement with the Standard Model predictions, without any evidence to go beyond it